Plugging effect of open-ended piles in sandy soil
Junyoung Ko and Sangseom Jeong

Abstract: This paper presents an experimental study of the plugging effect on the capacity of open-ended piles installed in sandy soil. Full-scale tests, including dynamic and static axial compression load tests, were carried out on three instrumented piles with different diameters (508.0, 711.2, and 914.4 mm). To measure the outer and inner shaft resistances acting on the piles, a double-walled system was utilized, with instrumented strain gauges on the outside and inside walls of the pile. The results of field tests show that the inner shaft resistance was mostly mobilized at the location between the pile tip and 18%–34% of the total plug length. It was found that the soil plugging in the lower portion has influence on the inner shaft resistance. In addition, it can be also demonstrated that the ratio of inner shaft resistance plus annulus load resistance to total resistance was decreased with increasing pile diameters. The results of these tests show that the relationship between the degree of plugging and pile diameter is clearly established. Direct observations of the soil plugs were made and used to quantify both the plug length ratio (PLR) and the incremental filling ratio (IFR). Based on this result, it was realized that the N value of the standard penetration test (SPT) is highly correlated with the IFR.

Key words: plugging effect, sand, pile diameter, open-ended pile, field load test.

Introduction

Numerous construction projects are currently under way in Korean urban and coastal areas such as harbour terminals, offshore grand bridges, and lifeline systems. Steel pipe piles are frequently used to support high-rise buildings and heavy structures for ensuring structural safety rather than service limit capacity. Steel pipe piles are also widely applied in civil engineering structures because of their high load bearing capacity, light weight, and outstanding workability. Substantial foundations are required for grand bridges and high-rise buildings, and large-diameter driven piles are frequently used in these projects.

Many specifications such as API (2007), FHWA (Hannigan et al. 1997), and AASHTO (2002) provide guidelines for plugging effects. However, current design methods to account for the plugging effect of steel pipe piles are primarily based on observations of model tests or small-diameter pile load tests. Therefore, these specifications have limits when applied to steel pipe piles of a large diameter.

A substantial amount of research exists on the plugging effect of open-ended piles in various areas, including soil parameters (Kishida and Isemoto 1977; Kraft 1991; Randolph et al. 1992), pile parameters (Klos and Tejchman 1981), and pile installation methods (Scehy 1961; Nauroy and Le Tirant 1983; Brucy et al. 1991).

Yamahara (1964) reported that a soil plug can be modelled as a thin disk element because the increment of radial strain on the soil plug can be neglected due to the high rigidity of the pile compared with that of the soil plug. Paikowsky and Whitman (1990) reported fundamental studies on the mechanism of the plugging effect in sand. Paik et al. (2003) reported on proposed empirical relationships between the plug load capacity, annulus load capacity, and shaft load capacity of open-ended piles based on model pile tests.

Recently, many design methods for the open-ended piles are based on the cone-penetration test (CPT) (Gavin and Lehane 2003; Lehane et al. 2005; Schneider et al. 2008; Xu et al. 2008). These CPT-based methods usually use the results of cone tip resistance ($q_c$) of CPTs to consider the plugging effect. A comprehensive study by Gavin and Lehane (2003) shows that shaft capacity of
open-ended piles may be expressed as a function of the incremental filling ratio (IFR), the CPT $q_c$ value, and the relative position of the pile toe in sand.

On the contrary, this study focuses on investigating the relationship between the plugging effect and the standard penetration test (SPT). The SPT-based method is chosen as another option in the engineering field, since the SPT is more commonly used to identify subsoil conditions in sandy soils.

As mentioned earlier in the text, significant work exists in the area of the plugging effect for small-diameter pipe piles ($\sim$300–500 mm in diameter). However, the medium- or large-diameter pipe piles (500 mm diameter or larger) are frequently used in practice, but available data of field load tests are very limited. Therefore, the main objective of this study is to investigate the plugging effect of open-ended piles through field load tests on full-scale piles. The result of field load tests can be useful for design of open-ended piles in engineering practice.

Methods available for plugging effect on open-ended piles

Steel pipe piles can be divided into two categories: open-ended piles and closed-ended piles. For larger diameter steel pipe piles
(500 mm in diameter or larger), the piles are installed as open-ended. During the initial pile driving, the soil enters the pile. As pile penetration increases, the open-ended piles fill with soil; if the interior soil column does not equal the pile penetration, this is called the plugging effect and the pile may behave as if it was closed-ended.

The plugging effect of a steel pipe pile can be divided into three conditions: unplugged; partially plugged; and fully plugged, as shown in Fig. 1. During the initial pile driving, the soil plug length in the pile is equal to the penetration depth, and the pile is in an unplugged condition (Fig. 1a). As pile penetration continues, inner shaft frictional resistance occurs between the soil plug and the inner pile. Because of this, the length of the soil plug becomes less than the penetration depth and the pile is partially plugged (Fig. 1b). Eventually, the pile penetrates into soil but the soil plug length does not change, thus creating a fully plugged condition (Fig. 1c).

The plugging effect can be quantified by using the plug length ratio (PLR) and the IFR. The PLR is defined as the ratio of the soil plug length to the penetration depth at the completion of pile driving. The PLR can be written as

\[
\text{PLR} = \frac{L_i}{D_i}
\]

where \(L_i\) is the soil plug length, and \(D_i\) is the penetration depth.

The IFR can be defined as the ratio of the increment of the soil plug length to the increment of pile penetration depth during pile driving. The IFR can be written as

Table 1. Physical properties of in situ soil.

<table>
<thead>
<tr>
<th>Soil</th>
<th>Fill</th>
<th>Sand</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total unit weight, (\gamma_i) (kN/m(^3))</td>
<td>17.6</td>
<td>18.0</td>
</tr>
<tr>
<td>Poisson’s ratio, (\mu_i)</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>Friction angle (°)</td>
<td>32</td>
<td>33</td>
</tr>
<tr>
<td>(N) value</td>
<td>8–18</td>
<td>12–27</td>
</tr>
</tbody>
</table>

**Fig. 4.** Soil profile with borehole and embedment for test piles: (a) subsurface soil profile; (b) \(N\) value from SPT.
where $\Delta L_i$ is the increment of soil pile length, and $\Delta D_i$ is the increment of pile penetration depth.

The bearing capacity of an open-ended pile under static compressive loading is the sum of the outer shaft resistance, $Q_{\text{out}}$, the annulus resistance, $Q_{\text{ann}}$, of the annular pile base, and the soil plug resistance, $Q_{\text{plug}}$, assuming that each component is independent (Fig. 2; modified from Matsumoto et al. 2007). Based on force equilibrium, the soil plug resistance, $Q_{\text{plug}}$, is the smaller value of either the inner shaft resistance, $Q_{\text{in}}$, or the bearing capacity of the soil beneath the plug base, $Q_{\text{base}}$.

**Field load test**

Field load tests were conducted at the Kwangyang plant construction site to investigate the plugging effect of open-ended piles in sandy soil. Emphasis was placed on analyzing the plugging effect from the pile to the surrounding sand; therefore, these tests were performed on three instrumented piles under various conditions such as pile diameter and pile length.
Site investigation

Due to the complexities of the plugging effect, a comprehensive geotechnical investigation was performed to define the soil profile and properties at the test site as accurately as possible. To identify the subsurface materials, a subsurface investigation was performed on two boreholes (BH-1 and BH-2) by using conventional sampling near the test piles. Figure 3 shows the site plan and the location of the field tests. Figure 4 shows an image of the subsurface soil profile with the borehole and embedment for the test piles.

The soil profile near the surface consists of 15 m of sand underlain by reclaimed land. The water table was 2.5 m below the surface of the ground level. The results of the SPTs indicate that sand deposits at 0–15 m were in a loose state, with SPT N values ranging from 8 to 18. The soil properties based on these site investigations are summarized in Table 1.

According to the Unified Soil Classification System (ASTM 2011), the sand is classified as poorly graded sand (SP) with
round angularity. The mineralogy of sand is primarily composed of quartz, calcium carbonate, feldspar, and others.

**Installed test piles**

The resistance of open-ended piles consists of three components: outer shaft resistance; toe resistance; and inner shaft resistance (or soil plug resistance). To measure all of these resistance components in open-ended piles, an instrumented double-walled pile system is necessary (Paik and Lee 1993; Choi and O’Neill 1997; Lehane and Gavin 2001). This system has been previously used in field load tests on 356 mm diameter piles by Paik et al. (2003).

A schematic representation of the instrumented piles is shown in Fig. 5. The test piles, TP-1, TP-2, and TP-3, have differing outer diameters of 508.0, 711.2, and 914.4 mm. The test piles were prefabricated in factories. The gap between the outer and inner pile was sealed with a thin membrane to prevent any intrusion of soil during the tests. Figure 5d shows the test piles welded between the outer and inner piles. All piles were driven with a DHK-13 hydraulic hammer (130 kN). The free-fall height of the hammer was 0.3 m. To prevent potential damages of strain gauges during pile driving, the lower free-fall height was applied.

This study utilized automated equipment for static load testing that included linear variable differential transformers (LVDTs), electrical resistance strain gauges, and vibration wire strain gauges. Pile settlement was measured at the pile head using two LVDTs that were attached to an independent reference frame. A total of 20 electrical resistance strain gauges and 12 vibration wire strain gauges were installed along the pile circumference every 90° to measure the inner and outer shaft resistances. The gauges were sealed with a thin membrane to prevent the intrusion of water. The output from these various sensors was simultaneously collected using a computer controlled data acquisition system.

The IFR was measured to investigate the plugging effect of open-ended piles in terms of the pile diameters during pile driving. A weighted wire was threaded through pre-drilled holes in the pile, thus allowing the IFR to be measured during pile driving. A researcher held the wire during pile driving process and measured the IFR after each increment of pile driving.

**Dynamic load test**

Dynamic load tests were performed to evaluate the bearing capacity of the piles at the end of initial driving (EOID). The objective of the dynamic load test was to investigate the drivability of piles with differing pile diameters and penetration depths.

The test piles were driven using a ram weight of 130 kN. The maximum hammer stroke was 0.5 m to prevent potential damage to the strain gauges during the pile driving process. Dynamic load tests were conducted following the ASTM D4945 protocol (ASTM 2013a). The instruments used for the dynamic tests included a set of pile driving analyzers, four accelerometers, and four strain transducers.

**Static load test**

Static load tests were conducted in compression and based on the ASTM D1143 protocol (ASTM 2013b). To investigate the setup effect, these tests were performed 45 days after the dynamic load tests. A total of 12 earth anchors were installed at the test site to serve as a reaction. A schematic representation of the loading system for the static load test is shown in Fig. 7. The instruments used for the static load tests included a load cell, a hydraulic jack, a pump, LVDTs, and beams. The maximum capacity of the load cell and the hydraulic jack was 7000 kN.

A set of H-beams were used for the load frame, consisting of two H-beams as the main beams (900 mm × 300 mm × 10 000 mm) and six H-beams as the support beams (300 mm × 300 mm × 8000 mm, 300 mm × 300 mm × 2000 mm). The maximum loads were 250% of the design loads. The loading and unloading were systematically carried out in five cycles and 10 steps. During the loading stage, each step lasted a minimum of 20 min, while the step duration was no less than 10 min during the unloading stage.

**Test results and discussion**

**PLR and IFR measurements**

Soil plug development can be quantified by measuring the soil plug height and calculating the PLR and IFR during the pile driving process. In general, the plugging criterion is defined by using an IFR. Incremental filling ratios of 0 and 100 mean that the pile is fully plugged and unplugged, respectively, and an IFR between 0 and 100 indicates a partially plugged condition.

Both the PLR and IFR were measured on three instrumented piles to investigate the plugging effect on different pile diameters. The measurement results are presented in Fig. 8 in terms of the depth versus both PLR and IFR. Test piles TP-1, TP-2, and TP-3 were considered to be partially plugged because the IFR of all piles were between 0 and 100. It was also shown that the PLR sharply decreased in the early stage of penetration (roughly 2.0–3.0 m) in all cases. As the pile driving process continued, the PLR of TP-1, TP-2, and TP-3 reached 0.44, 0.76, and 0.85 at the end of penetration, respectively. Based on these results, it is shown that the plugging effect of open-ended piles decreases with an increase of the pile diameter. This is consistent with most works by other researchers (e.g., Szechy 1959; Kishida 1967; Paikowsky 1989), which show that large-diameter pipe piles are typically not in a plugged condition but rather in a partially plugged condition.

There has been a great deal of study on IFR concerning the cone resistance of CPT and relative density. In general, previous research has shown that the IFR of driven piles gradually decreases with penetration depth and decreasing relative density (Klos and others).
However, less is known about IFRs with an SPT value. Therefore, the results of IFR measurements are evaluated by comparing them with the N value of a SPT. The effect of the results of the SPTs and the IFR on the installation plug resistance is investigated in Fig. 9.

The IFR significantly decreases with an increase of N in section a. This result shows that the IFR decreases regardless of soil conditions because the IFR in the first penetration is almost 100%. In sections b and d, the IFR increases with an increase of N, while the IFR decreases with a decrease of N in sections e and f. In section c, the IFR decreases when N is the same as the depth. These trends generally agree with previous research. As a rule, the IFR decreases with decreasing relative density in previous research. Skempton (1986) also proposed that the N value is proportional to the square of the relative density. Based on this, it can also be determined that the value of the SPT is highly correlated to the IFR.

Dynamic load test results

Dynamic load tests were performed to evaluate the bearing capacity of piles at the EOID and to verify the setup effect through comparison with the results of static load tests. The objective of the dynamic load tests was to investigate the drivability of piles with different pile diameters and penetration depths. Based on the results of the dynamic load tests, the allowable bearing capacity of piles is generally determined by using the following method: evaluate the failure load by applying Davisson’s offset line to the total bearing capacity obtained from a CAPWAP (GRL and Associates, Inc. 1997) analysis and then calculate the allowable bearing capacity by using 2.0 as the safety factor. The bearing capacity achieved by using a CAPWAP analysis and Davisson’s offset line is summarized in Table 2. The total and yield bearing capacities of TP-1, TP-2, and TP-3 were 1031, 2240, and 3100 kN according to the CAPWAP analysis and 800, 2230, and 3100 kN by means of Davison’s method, respectively.

To investigate the drivability of piles, the blow count with the penetration depth was measured at all three test piles. Figure 10 shows the penetration depth versus the penetration depth per blow. The penetration per blow for TP-1 was greater than TP-2 and TP-3 until a penetration depth of 4.5 m. After 4.5 m, the penetration per blow for TP-1 was very similar to TP-2 and TP-3.

In general, the drivability for open-ended piles depends on the soil plug in the pile (McCammon and Golder 1970; Brucy et al. 1991). According to previous findings reported by O’Neill and Raines (1991), Raines et al. (1992), and Paikowsky and Whitman (1990), the drivability for open-ended piles is almost same as that for the closed-ended piles when the penetration depth of the pile is approximately \( \frac{20}{H} - \frac{35}{H} \) times higher than the pile diameter in sand. In this study, however, all test piles were driven in medium sand layers and thus recognized as partially plugged piles, indicating that the pile penetration depth was estimated to be \( \frac{16}{H} \) times of the outside pile diameter. As a result, it is shown that the drivability for open-ended piles is highly dependent on the degree of soil plugging in the partially plugged conditions. The degree of soil plugging can be quantified in terms of the IFR during pile driving. As shown in Fig. 9, the IFR of TP-2 was always smaller than that of TP-3 in the case of the penetration depth over 8.0 m. This indicates that the degree of soil plugging of TP-2 was larger than that of TP-3 when a penetration depth is over 8.0 m. This is supported by the result shown in Fig. 10.

All test piles were initially set in unplugged conditions. As the pile driving continued, inner shaft resistance mobilized between the soil plug and the inner piles, depending on the degree of soil plugging. Because of the differences in the magnitude of mobilizing inner shaft resistance, the penetration per blow for TP-1 was initially greater than the others. The penetration per blow for TP-1 also decreased dramatically, but the penetration per blow for TP-2 and TP-3 varied slightly. This result shows that TP-1 achieved a...
plugged condition but TP-2 and TP-3 were at unplugged conditions. Based on this result, it can be determined that the degree of soil plugging depends on the pile diameters.

**Static load test results**

A series of static load tests was performed in the field (three cases). The axial load distribution profiles were obtained by analyzing the measured strain gauge data along each pile. The pile settlement was directly measured by LVDTs located in the pile head. The information obtained by the static load tests played a significant role in understanding the bearing capacity in both plugged and unplugged conditions.

Figure 11 shows the load–settlement curve for the test piles. The ultimate bearing capacities of piles TP-1, TP-2, and TP-3 were 1000, 2000, and 3000 kN, respectively.

The axial load distributions in the inner and outer piles were measured for the loading steps. Figure 12 shows the axial load distribution curves for six test piles; three inner piles and three outer piles. The figure shows that the resistance components of open-ended piles were separated. As shown in Figs. 12a, 12c, and

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**Table 2. Bearing capacity from dynamic load tests.**

<table>
<thead>
<tr>
<th>Pile No.</th>
<th>Penetration depth (m)</th>
<th>Test type</th>
<th>CAPWAP analysis</th>
<th>Davisson’s method</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Skin friction (kN)</td>
<td>End bearing capacity (kN)</td>
<td>Total capacity (kN)</td>
<td>Yield bearing capacity (kN)</td>
</tr>
<tr>
<td>TP-1</td>
<td>8.6</td>
<td>EOID</td>
<td>711</td>
<td>320</td>
<td>1031</td>
<td>800</td>
</tr>
<tr>
<td>TP-2</td>
<td>11.4</td>
<td>EOID</td>
<td>1580</td>
<td>660</td>
<td>2240</td>
<td>2230</td>
</tr>
<tr>
<td>TP-3</td>
<td>15.5</td>
<td>EOID</td>
<td>2149</td>
<td>951</td>
<td>3100</td>
<td>3100</td>
</tr>
</tbody>
</table>

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**Fig. 9.** Variation of IFR with N value.

**Fig. 10.** Variation of drivability with penetration depth.

**Fig. 11.** Load–settlement curve.
The inner shaft resistance was not mobilized in the early loading step. As the loading increased, some of the applied load was transferred to the soil plug. As shown in Figs. 12b, 12d, and 12f, the curves of the outer shaft resistance were of general form. However, the outer shaft resistance at the lower portion of the outer pile was due to tensile load. Because of the difference in magnitude between the outer and inner shaft resistances, the double-walled pile displayed differential settlement despite the welding. The differential settlement between the inner and outer piles was not measured by using LVDTs at the pile tip. Therefore, the differential settlement was calculated indirectly by using the performed load-transfer tests. Here, the differential settlement was the minus value between the pile head settlement and elastic settlement, which was measured from the strain gauge readings along the pile embedment. Based on this, calculated inner and outer tip settlements were calculated in Table 3. As shown in Fig. 13, the inner and outer shaft resistances are mobilized along the inner pile and outer pile, respectively. In general, the settlement of inner pile was larger than the settlement of outer pile because the outer shaft resistance was larger than the inner shaft resistance.

Influence zone for inner shaft resistance

Paikowsky (1990) reported that the dense layer formed in the bottom part of the soil plug. The soil plugging can be quantified by
measuring the inner shaft resistance of the piles. As shown in Figs. 12a, 12c, and 12e, the results of static load tests show that most of the inner shaft resistance was mobilized within a distance of 1.3–2.3 m from the tip, at the ultimate loading state. Further discussion can be made by analyzing soil plugging index with respect to the pile inner diameter. The soil plugging index (SPI) is defined as

\[
SPI = \frac{I_{is}}{I_{i}} \times 100
\]

where \(I_i\) is the soil plug length, and \(I_{is}\) is the length of mobilizing inner shaft resistance.

The inner shaft resistance occurs nearby the pile tip. The influence zone of the inner shaft resistance can be quantified by the axial load distribution of inner piles. The proposed SPI is a function of the inner pile diameter. The length of mobilizing inner shaft resistance is obtained as follows:

\[
I_{is} = \frac{I_d(SPI)}{100}
\]

The actual mobilizing inner shaft resistance can be obtained by using the obtained \(I_{is}\).

\[
Q_{is} = f_{is}A_{is} = f_{is} \pi D_i I_{is}
\]

where \(Q_{is}\) is the actual mobilizing inner shaft resistance; \(f_{is}\) is the unit inner shaft resistance; \(A_{is}\) is the area of the mobilizing inner shaft resistance; and \(D_i\) is the inner pile diameter.

For comparison, the SPI calculated from the work by Paik et al. (2003) is also presented. Figure 14 shows variation of SPI with pile inner diameter. The result shows that the inner shaft resistance was mostly mobilized at the location between the pile tip and 18%–34% of the total plug length. It was also found that the SPI linearly decreases with increasing the pile inner diameter, indicating that the soil plugging in the lower portion has influence on the inner shaft resistance.

**Base and shaft load capacity**

Table 4 shows the measured values of the annulus load resistance, inner shaft resistance, and outer shaft resistance of three test piles. The table contains the results of both the static load tests and the dynamic load tests (CAPWAP analysis). The results of dynamic load tests were separated into end bearing (gross section) and shaft resistance (assumed outer shaft resistance). However, the results of static load tests were separated into inner shaft, outer shaft, and annulus load resistance. Therefore, it was assumed that the inner shaft and annulus load resistance for the static load tests were the same as the end bearing resistance for the dynamic load tests.

The ultimate bearing capacities for the static load tests were similar to those for the dynamic load tests, and the setup effect did not occur in this study. The portions of inner shaft and annulus load resistance for the static load tests were 42.0%, 41.7%, and 29.7% in TP-1, TP-2, and TP-3, respectively. This shows that the ratio of the inner shaft resistance and the annulus resistance to the total resistance was decreased with an increase of pile diameters. However, it also shows that the portion of the end bearing for the dynamic load test was ~30% in all cases. Based on this result, the static load test was shown to be capable of reflecting the behavior of the plugging effect.

As shown in Fig. 15, TP-2 had the largest unit annulus load resistance when the same settlement occurred. The \(N\) value ranged from 15 to 18 at the TP-2 tip, showing the most stiff soil conditions among TP-1, TP-2, and TP-3 test piles. It was shown that the unit annulus load resistance was influenced by soil condition at the pile tip. In addition, this study is focused on the plugging effect on the inner shaft resistance. Therefore, Fig. 16 is added to investigate the effect of the IFR on the inner shaft resistance. As shown in Fig. 16, the unit inner shaft resistance was increased with decreasing
IFR. It was found that the effect of the IFR was related to the inner shaft resistance.

Conclusions

The open-ended piles are widely used in practice, but reliable information available on the plugging effect with pile diameters is still limited. The main objective of this study was to investigate the plugging effect of open-ended piles driven into the medium sand with $N$ values ranging from 10 to 20. Limited data obtained from field pile tests were collected, and an empirical equation for estimating the base load capacity of open-ended piles was proposed based on the test data. For open-ended piles embedded in medium sand soil, comparative studies have clearly demonstrated the important plugging effect for friction piles rather than end-bearing piles. Full-scale tests that include dynamic and static axial compression load tests were carried out on three instrumented piles with different diameters (508.0, 711.2, and 914.4 mm). Direct observations on the soil plugs were made and used to quantify the PLR and the IFR. The results of full-scale tests and direct observation are useful for researchers interested in medium- or large-diameter pipe piles (500 mm diameter or larger) in sandy soil. Based on the findings of this study, the following conclusions can be drawn:

1. The plugging effect of the open-ended piles can occur with varying degrees of soil plugging. Also, to investigate the drivability of the piles, blow counts and penetration depths were measured on the three test piles. Inner shaft resistance mobilized between the soil plug and the inner piles, depending on the degree of soil plugging. Because of the difference in the magnitude of the mobilizing inner shaft resistance, the penetration per blow for TP-1 was initially greater than the others. In addition, the penetration per blow for TP-1 dramatically decreased, while the penetration per blow for TP-2 and TP-3 varied slightly. This result shows that TP-1 was initially at a nearly plugged condition, but TP-2 and TP-3 were at unplugged conditions. Based on these results, it can be clearly demonstrated that the plugging effect of the open-ended piles decreases with an increasing pile diameter.

2. The results of the IFR measurements were evaluated by comparing them with the $N$ values of the SPTs. It was realized that the $N$ value of the SPT is highly correlated to the IFR. This trend is in general agreement with previous research. The IFR generally decreases with decreasing relative density in previous research (Kloos and Tejchman 1977; De Nicola and Randolph 1997; Paik et al. 2003). Skempton (1986) proposed that the $N$ value is proportional to the square of the relative density. Therefore, the variations of the IFR are closely related to the $N$ value of the soil.
3. Based on the results of the static load tests, it can be determined that most of the inner shaft resistance at the ultimate loading state was mobilized within a distance of 1.3–2.3 m, as measured from the pile tip. The results of field tests show that the inner shaft resistance was mostly mobilized at the location between the pile tip and 18%–34% of the total plug length. It was also found that the SPI linearly decreases with increasing the pile inner diameter, indicating that the soil plugging in the lower portion has influence on the inner shaft resistance.

4. The portions of the inner shaft resistance plus annulus load resistance to total resistance for the static load tests were 42.0%, 41.7%, and 29.7% in TP-1, TP-2, and TP-3, respectively. It can be determined that the ratio of the inner shaft resistance and the annulus load resistance to the total resistance was decreased with an increase in pile diameters.

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